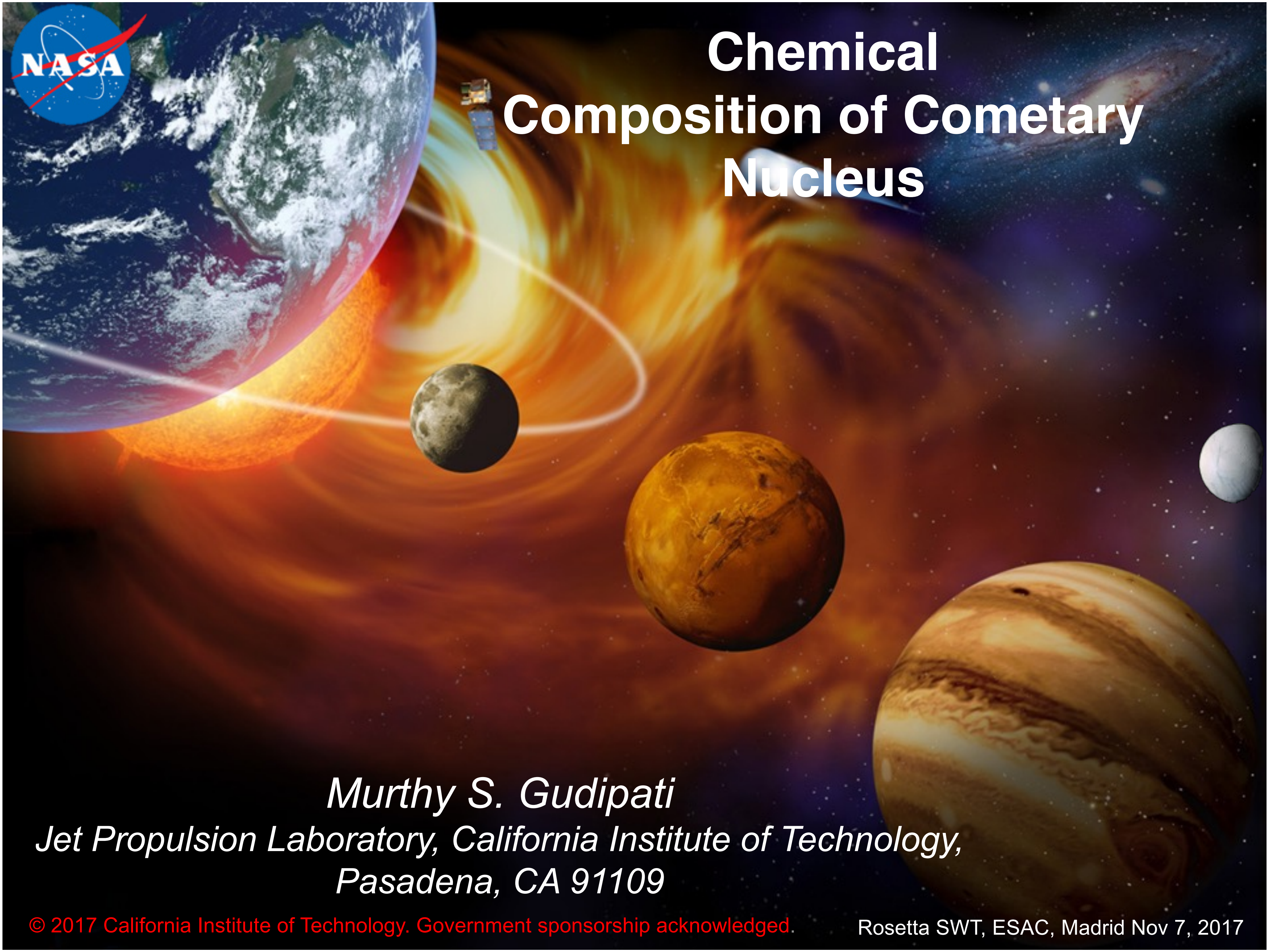

# Chemical Composition of Cometary Nucleus


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*Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109*




Rosetta SWT, ESAC, Madrid Nov 7, 2017

# Physical Composition of Comets

# Comet Physical Composition

Gas ($H_2O$, $CO_2$, and Super Volatiles)

Dust (Silicate Grains) and Refractory Organics

Water (in the form of Ice – major component)

**The Elephant in the Room: How these three components are put together in a comet's nucleus?**

# Density

*Icarus 277 (2016) 257–278*

The global shape, density and rotation of Comet 67P/Churyumov-Gerasimenko from preperihelion Rosetta/OSIRIS observations

L. Jorda[a,*], R. Gaskell[b], C. Capanna[a], S. Hviid[c], P. Lamy[a], J. Ďurech[d], G. Faury[e], O. Groussin[a], P. Gutiérrez[f], C. Jackman[g], S.J. Keihm[h], H.U. Keller[i], J. Knollenberg[c], E. Kührt[c], S. Marchi[j], S. Mottola[c], E. Palmer[b], F.P. Schloerb[k], H. Sierks[l], J.-B. Vincent[l], M.F. A'Hearn[m], C. Barbieri[n], R. Rodrigo[o,p], D. Koschny[q], H. Rickman[r,s], M.A. Barucci[t], J.L. Bertaux[u], I. Bertini[v], G. Cremonese[w], V. Da Deppo[x], B. Davidsson[r], S. Debei[y], M. De Cecco[z], S. Fornasier[t], M. Fulle[A], C. Güttler[l], W.-H. Ip[B], J.R. Kramm[l], M. Küppers[C], L.M. Lara[f], M. Lazzarin[n], J.J. Lopez Moreno[f], F. Marzari[n], G. Naletto[D,x,v], N. Oklay[l], N. Thomas[E], C. Tubiana[l], K.-P. Wenzel[F]

**Density = 532 ± 7 kg $m^{-3}$**

Crystalline $CO_2$ (30 K) = ~1200 kg $m^{-3}$
Crystalline water-ice = 920 kg $m^{-3}$
Amorphous water-ice = ~500 - 800 kg $m^{-3}$
Refractory Organics = ~600 kg $m^{-3}$
Carbonaceous chondrites = ~3000 to 3700 kg $m^{-3}$

# Thermal Inertia

Science, 349, aab0464, 2015

COMETARY SCIENCE

## Thermal and mechanical properties of the near-surface layers of comet 67P/Churyumov-Gerasimenko

T. Spohn,[1*] J. Knollenberg,[1] A. J. Ball,[2] M. Banaszkiewicz,[3] J. Benkhoff,[2] M. Grott,[1] J. Grygorczuk,[3] C. Hüttig,[1] A. Hagermann,[4] G. Kargl,[5] E. Kaufmann,[4] N. Kömle,[5] E. Kührt,[1] K. J. Kossacki,[6] W. Marczewski,[3] I. Pelivan,[1] R. Schrödter,[1] K. Seiferlin[7]

Thermal and mechanical material properties determine comet evolution and even solar system formation because comets are considered remnant volatile-rich planetesimals. Using data from the Multipurpose Sensors for Surface and Sub-Surface Science (MUPUS) instrument package gathered at the Philae landing site Abydos on comet 67P/Churyumov-Gerasimenko, we found the diurnal temperature to vary between 90 and 130 K. The surface emissivity was 0.97, and the local thermal inertia was 85 ± 35 J $m^{-2}$ $K^{-1}s^{1/2}$. The MUPUS thermal probe did not fully penetrate the near-surface layers, suggesting a local resistance of the ground to penetration of >4 megapascals, equivalent to >2 megapascal uniaxial compressive strength. A sintered near-surface microporous dust-ice layer with a porosity of 30 to 65% is consistent with the data.

**Thermal Inertia: 85±35 J $m^{-2}K^{-1}s^{-1/2}$**

Thermal gradient?
Is Cometary Nucleus Thermally Equilibrated?
Is it 40 K (KBOs), or ?

# Surface

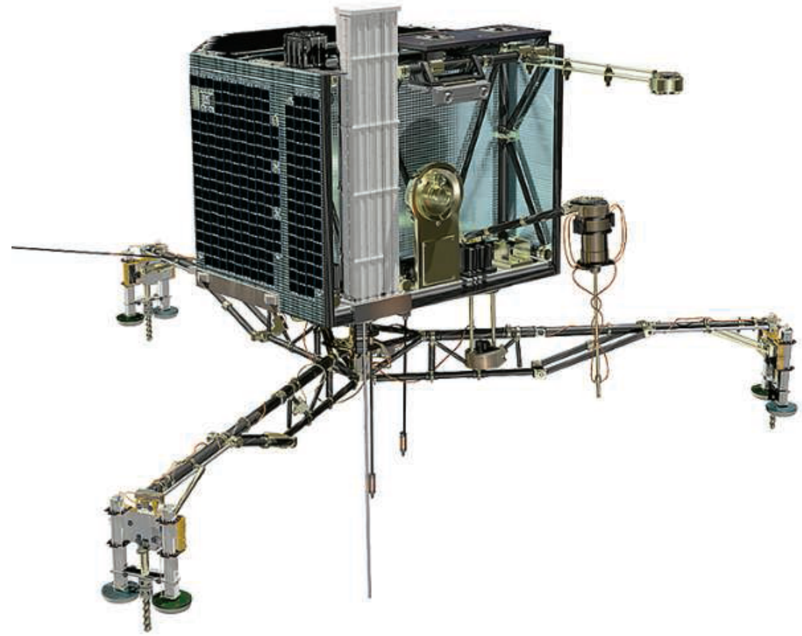
Science, 349, aaa9816, 2015

COMETARY SCIENCE

## The landing(s) of Philae and inferences about comet surface mechanical properties

Jens Biele,[1*] Stephan Ulamec,[1] Michael Maibaum,[1] Reinhard Roll,[3] Lars Witte,[2] Eric Jurado,[9] Pablo Muñoz,[5,12] Walter Arnold,[10] Hans-Ulrich Auster,[6] Carlos Casas,[5,12] Claudia Faber,[4] Cinzia Fantinati,[1] Felix Finke,[1] Hans-Herbert Fischer,[1] Koen Geurts,[1] Carsten Güttler,[3] Philip Heinisch,[6] Alain Herique,[8] Stubbe Hviid,[4] Günter Kargl,[7] Martin Knapmeyer,[4] Jörg Knollenberg,[4] Wlodek Kofman,[8] Norbert Kömle,[7] Ekkehard Kührt,[4] Valentina Lommatsch,[1] Stefano Mottola,[4] Ramon Pardo de Santayana,[5,12] Emile Remetean,[9] Frank Scholten,[4] Klaus J. Seidensticker,[4] Holger Sierks,[3] Tilman Spohn[4]

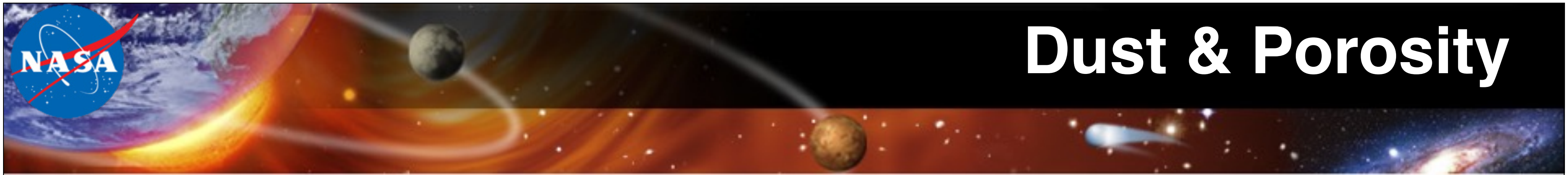
The Philae lander, part of the Rosetta mission to investigate comet 67P/Churyumov-Gerasimenko, was delivered to the cometary surface in November 2014. Here we report the precise circumstances of the multiple landings of Philae, including the bouncing trajectory and rebound parameters, based on engineering data in conjunction with operational instrument data. These data also provide information on the mechanical properties (strength and layering) of the comet surface. The first touchdown site, Agilkia, appears to have a granular soft surface (with a compressive strength of 1 kilopascal) at least ~20 cm thick, possibly on top of a more rigid layer. The final landing site, Abydos, has a hard surface.



~20 cm granular (soft)
Below hard crust??

How thick is the soft dust – cm range or m range?
Is there a “harder crust” below?

Science, 349, aab0639, 2015


COMETARY SCIENCE

# Properties of the 67P/Churyumov-Gerasimenko interior revealed by CONSERT radar

Wlodek Kofman,[1] Alain Herique,[1] Yves Barbin,[2] Jean-Pierre Barriot,[3] Valérie Ciarletti,[4] Stephen Clifford,[5] Peter Edenhofer,[6] Charles Elachi,[7] Christelle Eyraud,[15] Jean-Pierre Goutail,[4] Essam Heggy,[7,17] Laurent Jorda,[12] Jérémie Lasue,[14] Anny-Chantal Levasseur-Regourd,[13] Erling Nielsen,[8] Pierre Pasquero,[1] Frank Preusker,[16] Pascal Puget,[1] Dirk Plettemeier,[9] Yves Rogez,[1] Holger Sierks,[8] Christoph Statz,[9] Hakan Svedhem,[10] Iwan Williams,[11] Sonia Zine,[1] Jakob Van Zyl[7]

The Philae lander provides a unique opportunity to investigate the internal structure of a comet nucleus, providing information about its formation and evolution in the early solar system. We present Comet Nucleus Sounding Experiment by Radiowave Transmission (CONSERT) measurements of the interior of Comet 67P/Churyumov-Gerasimenko. From the propagation time and form of the signals, the upper part of the "head" of 67P is fairly homogeneous on a spatial scale of tens of meters. CONSERT also reduced the size of the uncertainty of Philae's final landing site down to approximately 21 by 34 square meters. The average permittivity is about 1.27, suggesting that this region has a volumetric dust/ice ratio of 0.4 to 2.6 and a porosity of 75 to 85%. The dust component may be comparable to that of carbonaceous chondrites.

Dust/Ice = 0.4 – 2.6
Porosity = 75 -85%

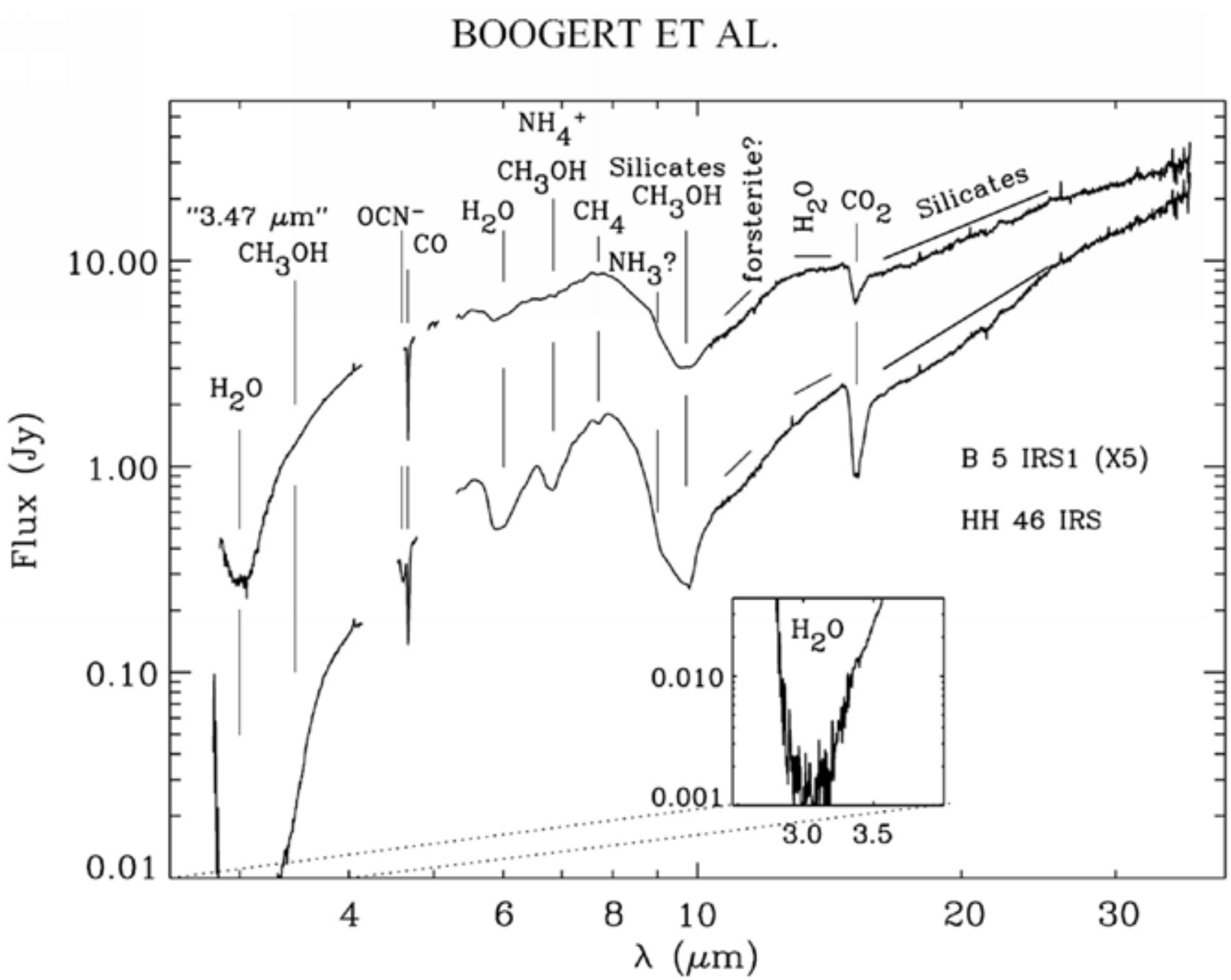
How accurate?

**What is Dust (We need a common definition)**
**Carbonaceous Chondrites? Silicates only? Refractory Organics?**
**Including Ice Particles?**

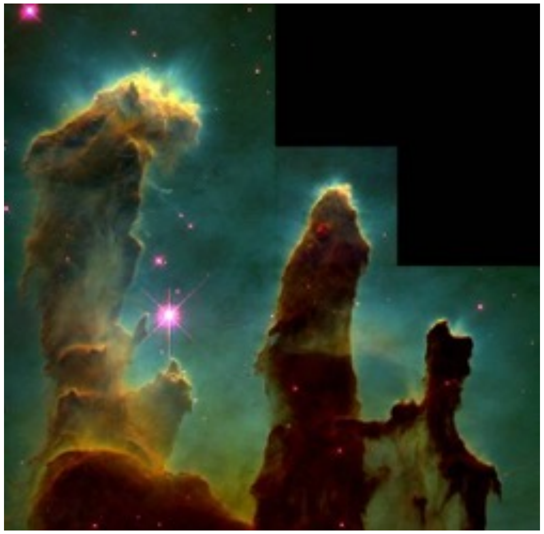
# Chemical Composition of Comets

# Interstellar Ice Grains: Loaded with Organics

## Amorphous Interstellar Ices



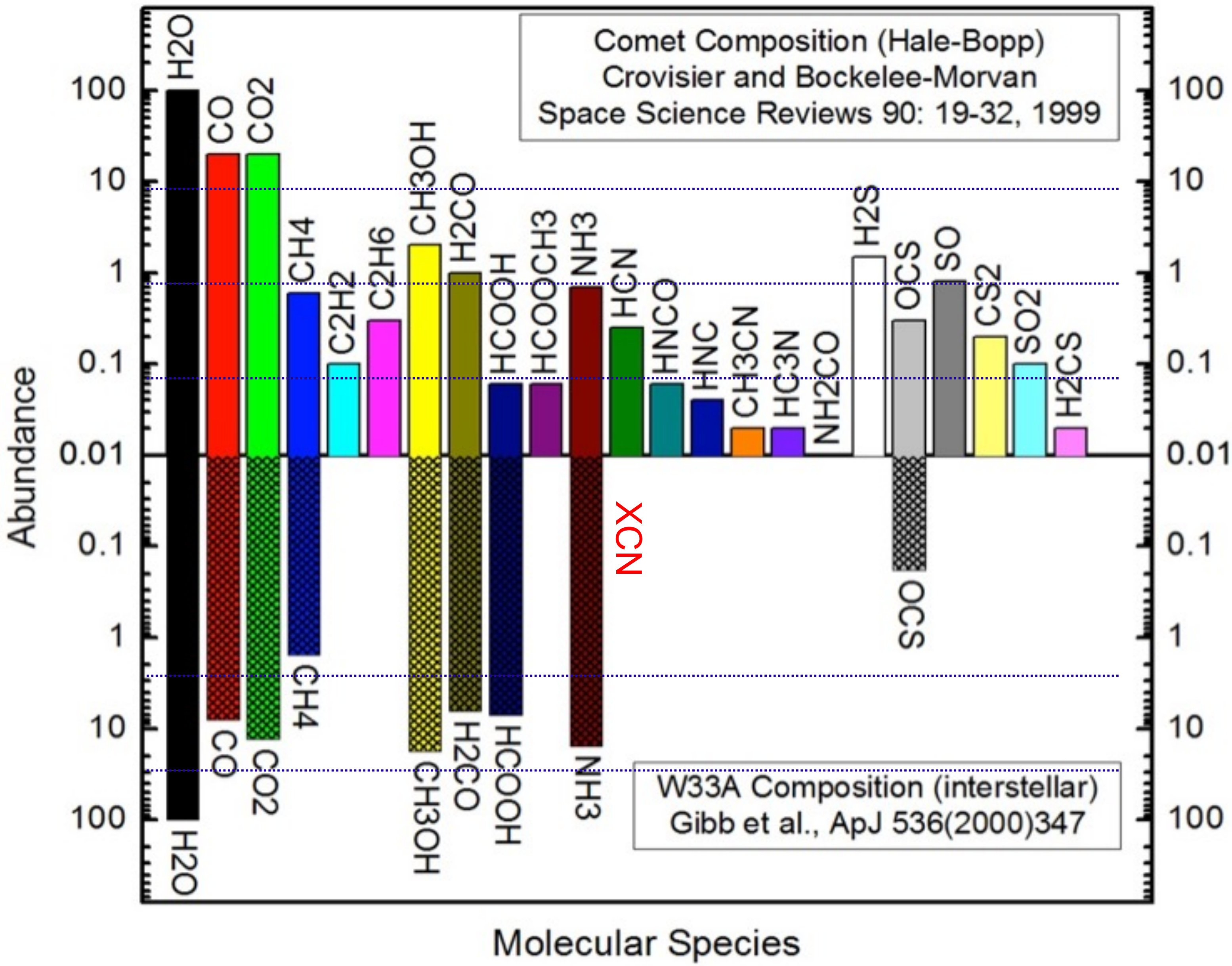

Star-forming Regions / Protostars



Dense Molecular Clouds (The Eagle Nebulae)

**Oort Cloud Comets – Similar Composition?**

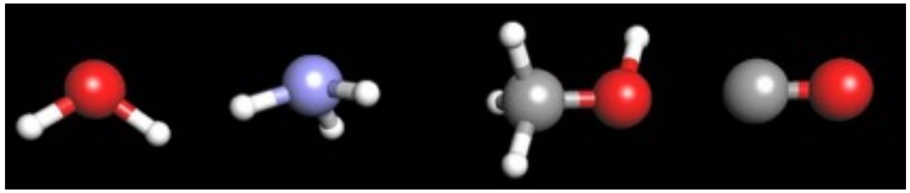
# Similar Composition: Comets and Interstellar Ice Grains



# Complex Organics – How and Where From?

# Refractory/Complex Organics: Where and How they are formed?

Cryogenic Cosmic Ices

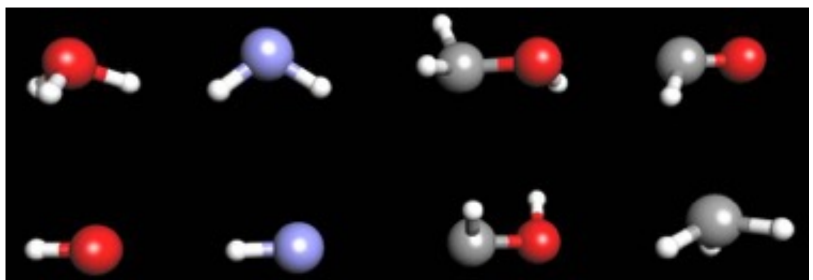


Raw Material
$H_2O$, $NH_3$, $CH_3OH$, CO

*Photons/Electrons*
*Cosmic Rays*
*Debris/Collisions*

*Temperature*

Radicals, Ions, Electrons, & Molecules

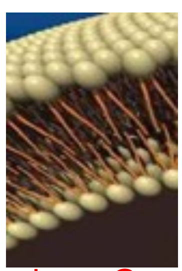


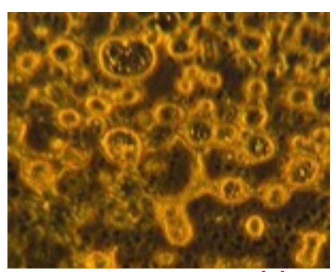
Building Blocks
Atoms, Radicals & Ions

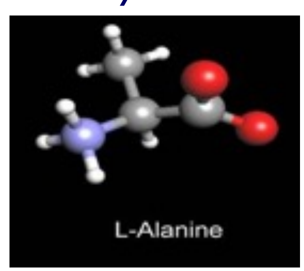
*Temperature*

*Photons/Electrons*
*Cosmic Rays*
*Debris/Collisions*

Amino Acids, Micelles, etc.





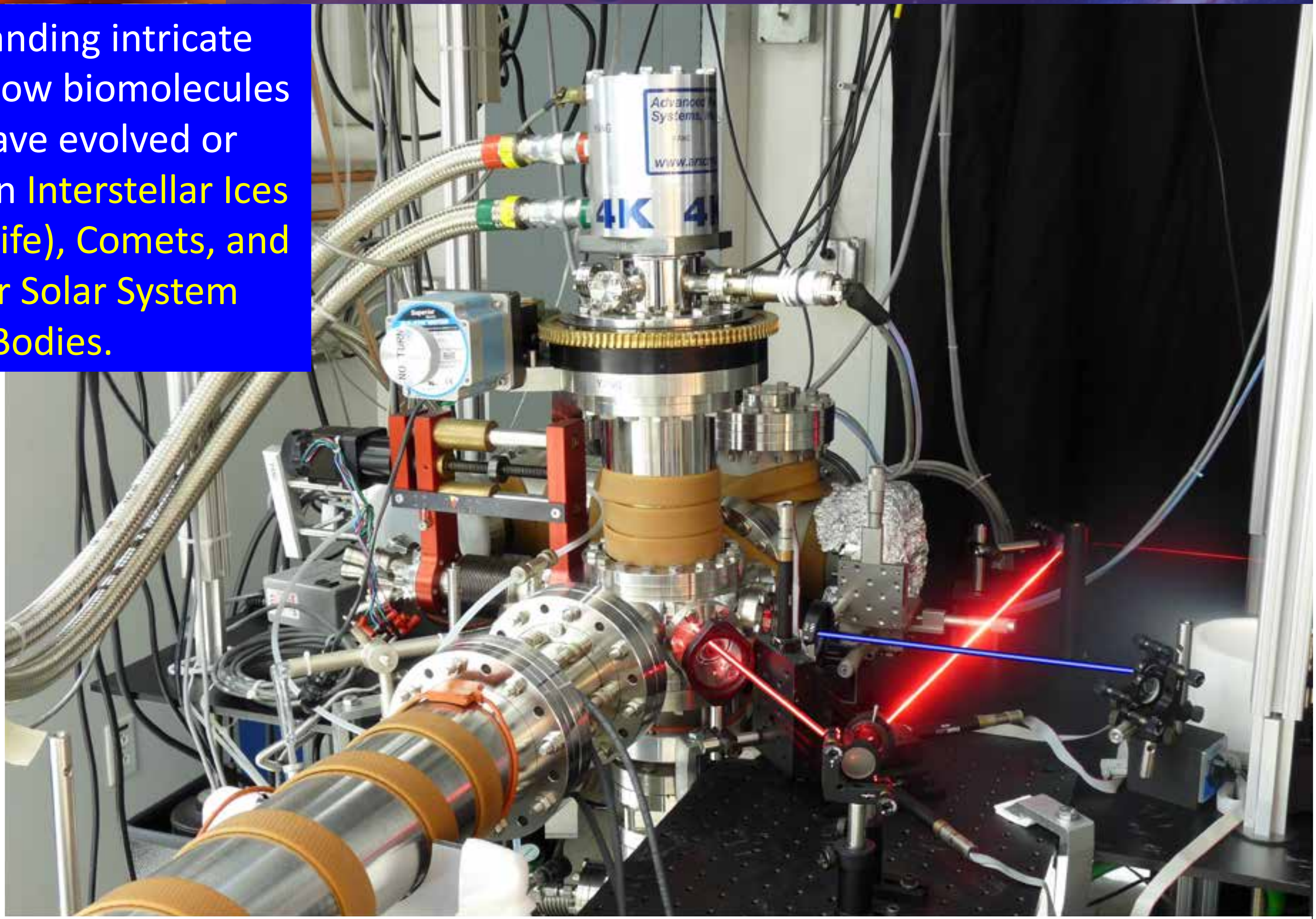



Biomolecules
Amino Acids etc.

# Understanding Prebiotic Chemistry in Comets

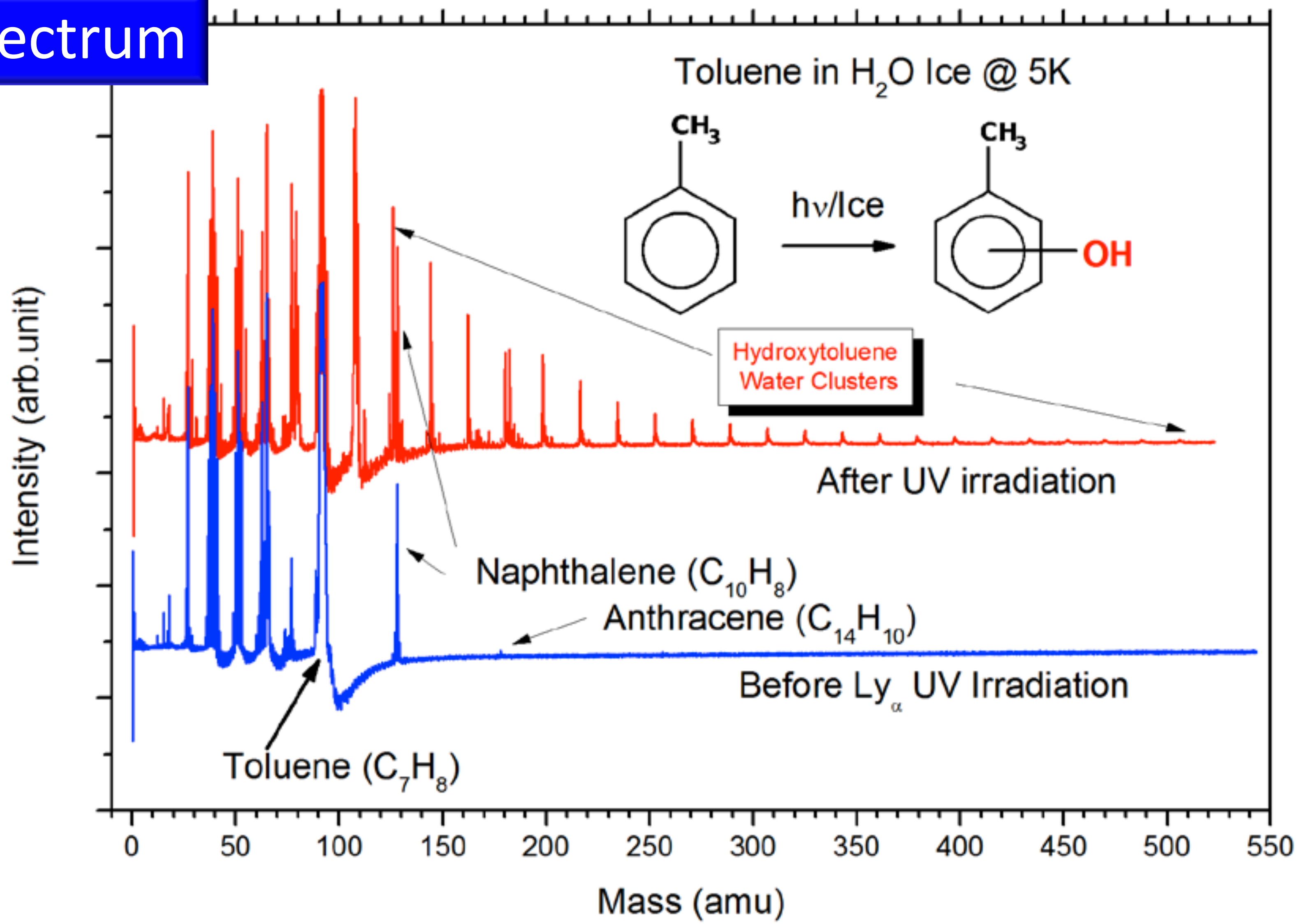
## At Murthy's Ice Spectroscopy Lab (ISL) @ JPL

Understanding intricate details of how biomolecules could have evolved or degraded in Interstellar Ices (Origin of Life), Comets, and on other Solar System Bodies.



# Oxygenation of Organics in Ices under Radiation

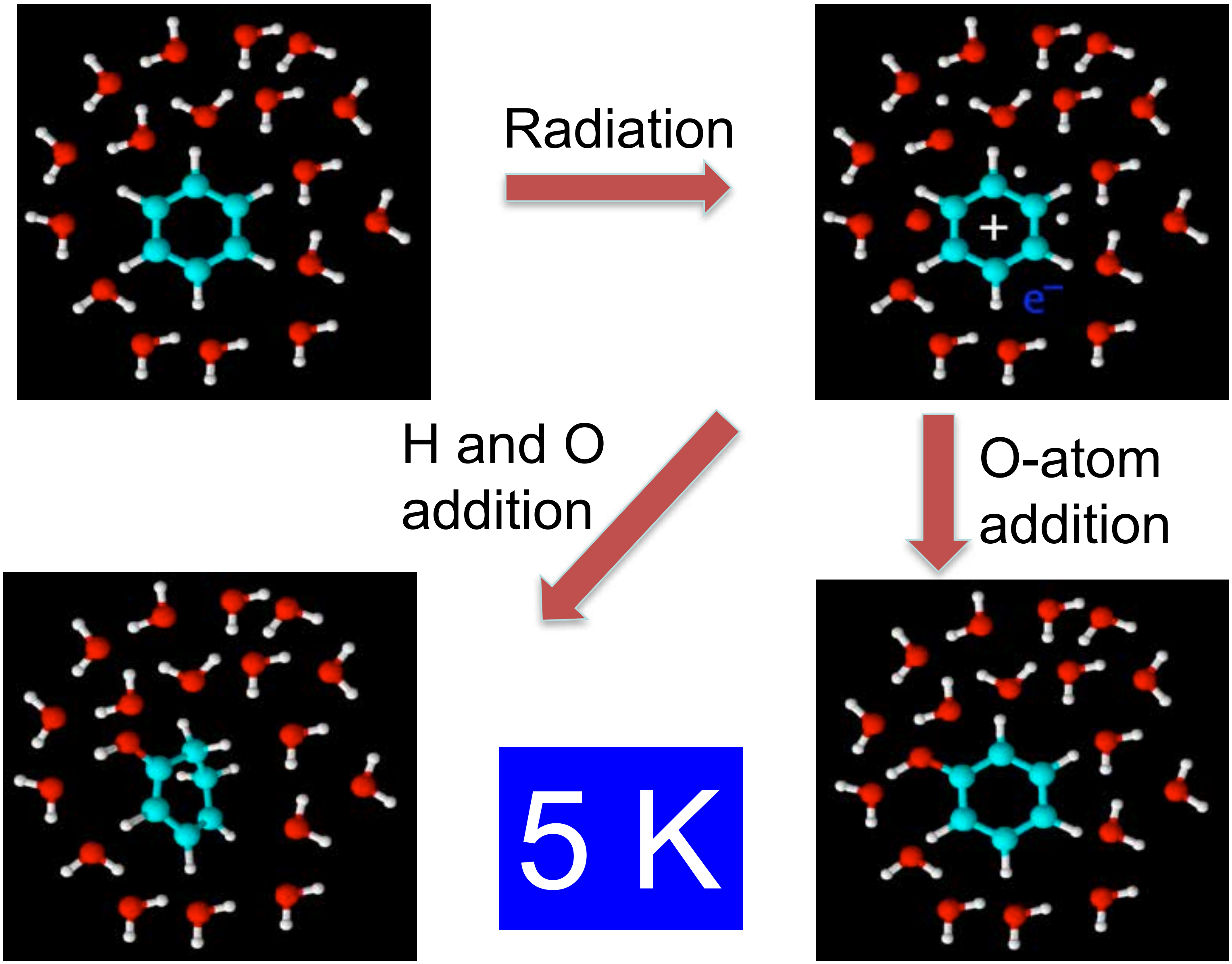
## 2S-LAIMS Spectrum




Gudipati & Yang ApJL 756, L24, 2012

Even under coldest interstellar conditions

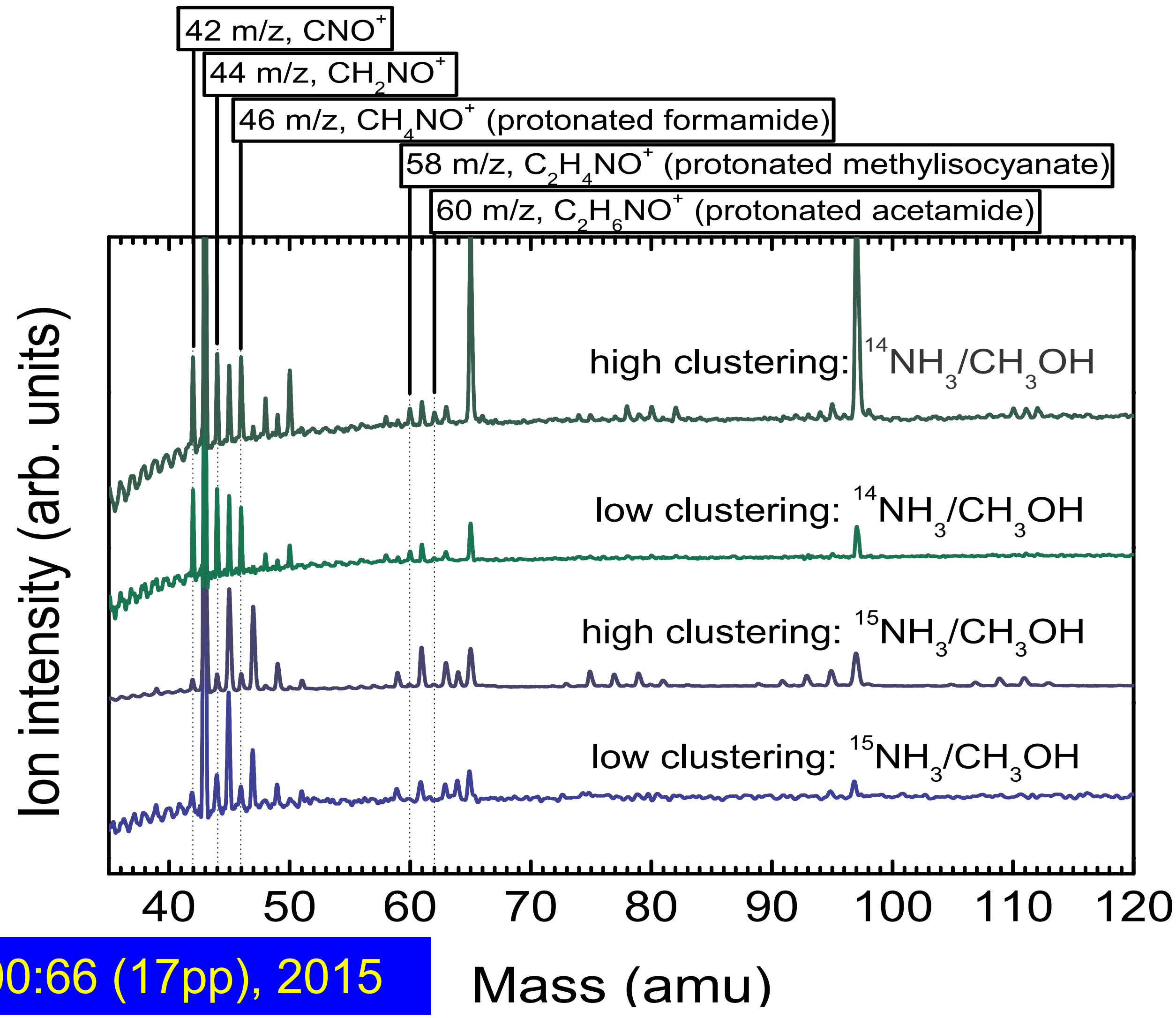
# Ionization-Mediated Radiation-Chemistry in Ices



# Realistic Cometary/Interstellar Ice Analogs

## Snapshots/Scooping the Evolution of Astrophysical Ice Analogs

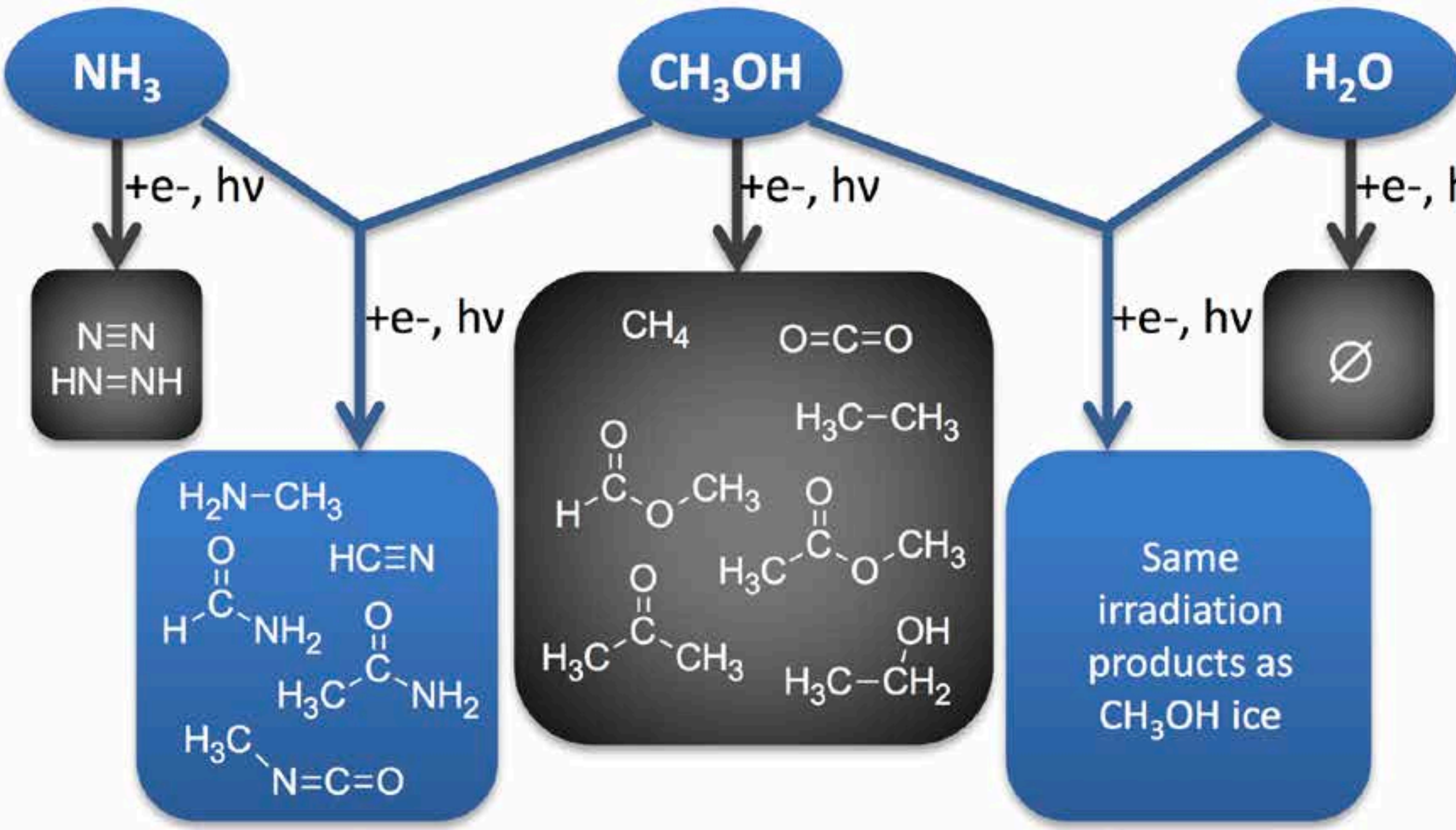
Interstellar / Cometary Ice Analogs Produce Key Building Blocks Of Life upon Radiation Processing




Henderson and Gudipati ApJ - 800:66 (17pp), 2015

# Molecules found in interstellar ice analogs

## Irradiation Products of Single and Dual-Component Ices, 5 K




**Many of these molecules are detected by Rosetta-ROSINA**

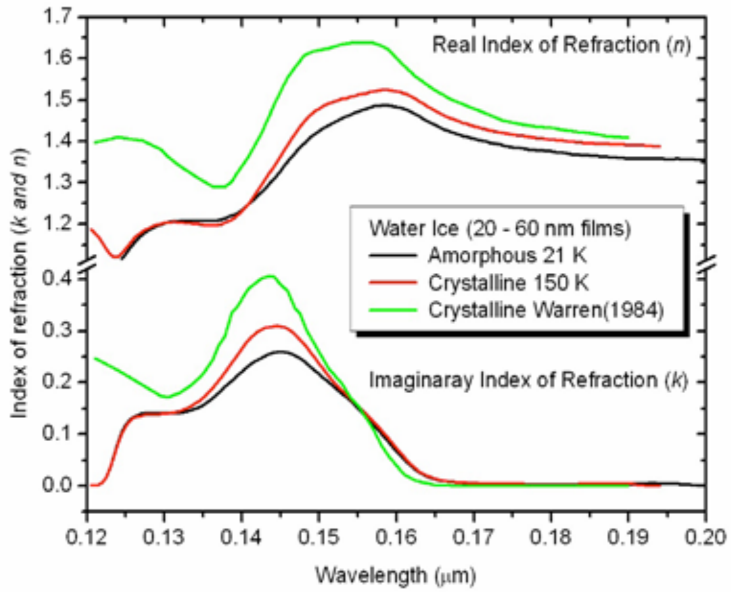
**$NH_3$ less reactive than $CH_3OH$ under radiation**

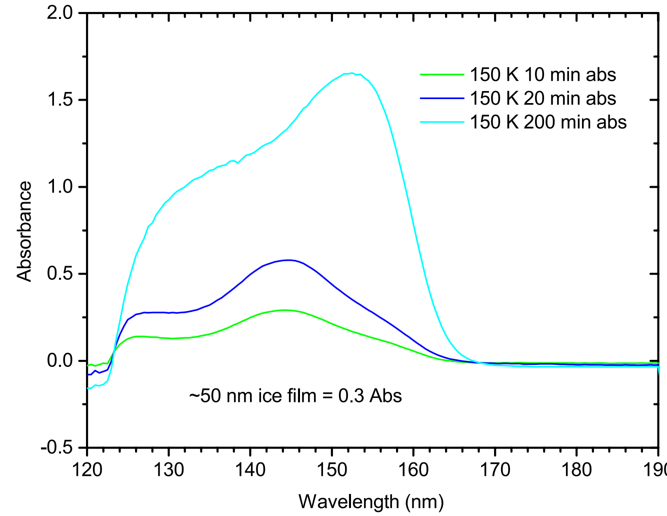
# Complex Organics:
# Already formed in Molecular Clouds

## How are Super Volatiles Trapped in $H_2O$ Ice?

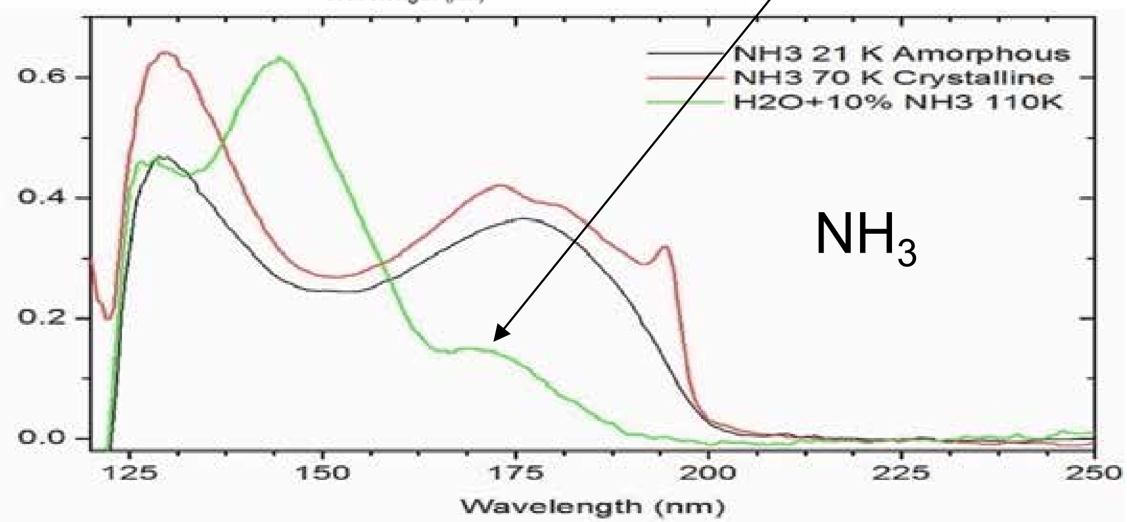
# Ice Composition VUV Studies

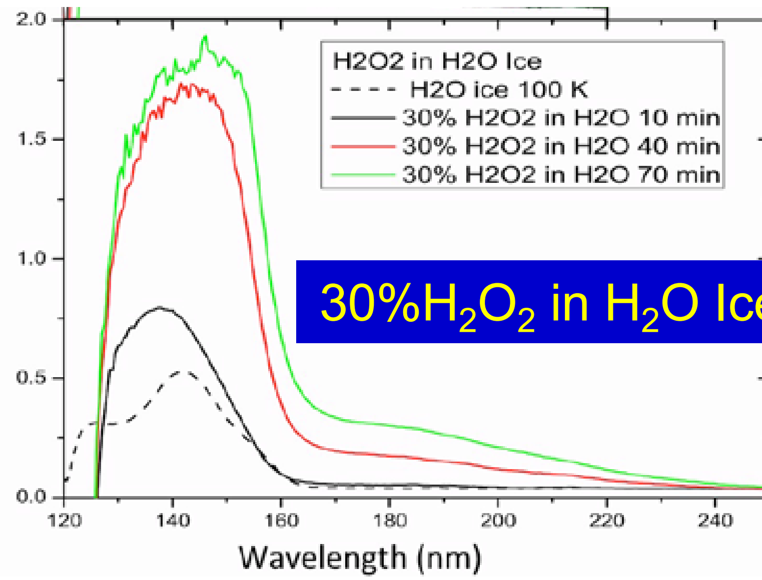
Absorbance of $H_2O$ Ice




Strongly Bonded

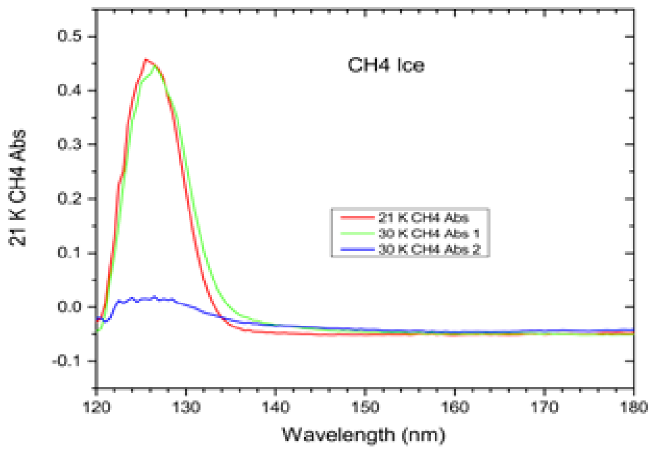


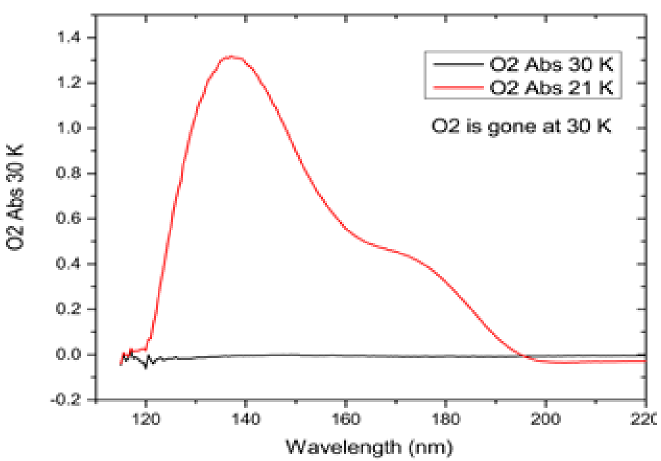




Top: VUV Optical Constants of Pure $H_2O$ Ice
Bottom: Absorption Spectra of $NH_3$ and $H_2O$ ice with 10%$NH_3$

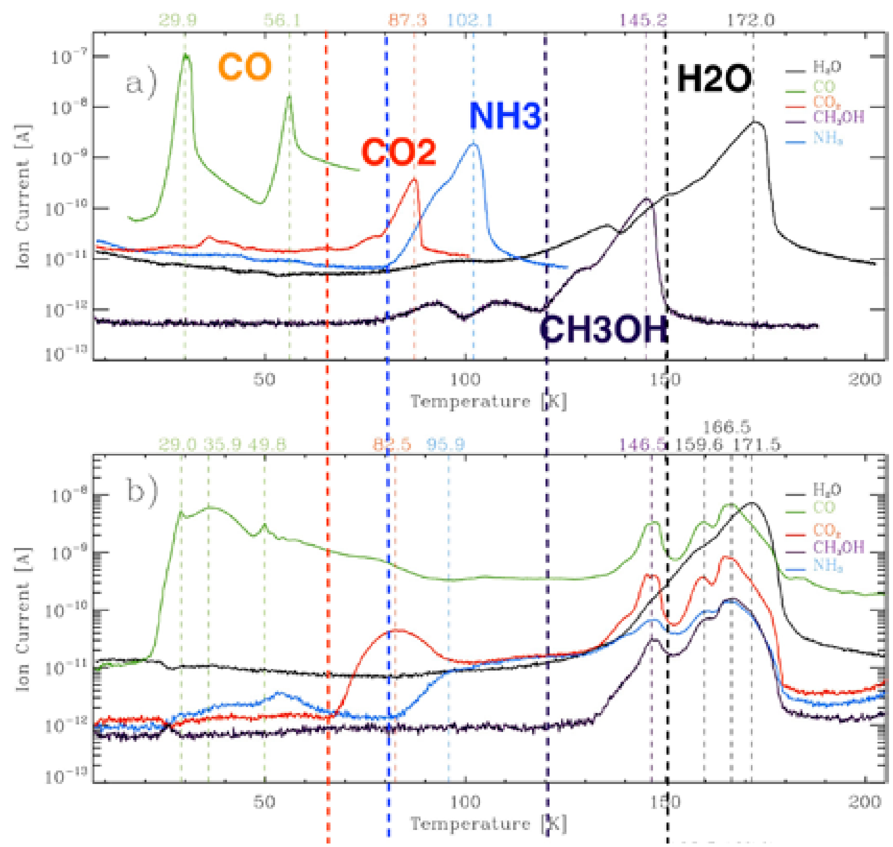
# Depletion Temperatures of Volatiles

Crystalline $H_2O$ Ice <160 K; Amorphous $H_2O$ Ice <<80 K
$CO_2$ Ice <70 K; Super Volatiles ~30 K




Gudipati et al., (NIST, VUV) – to be published




Martin-Domenech et al., *A & A* **2014,** *564*

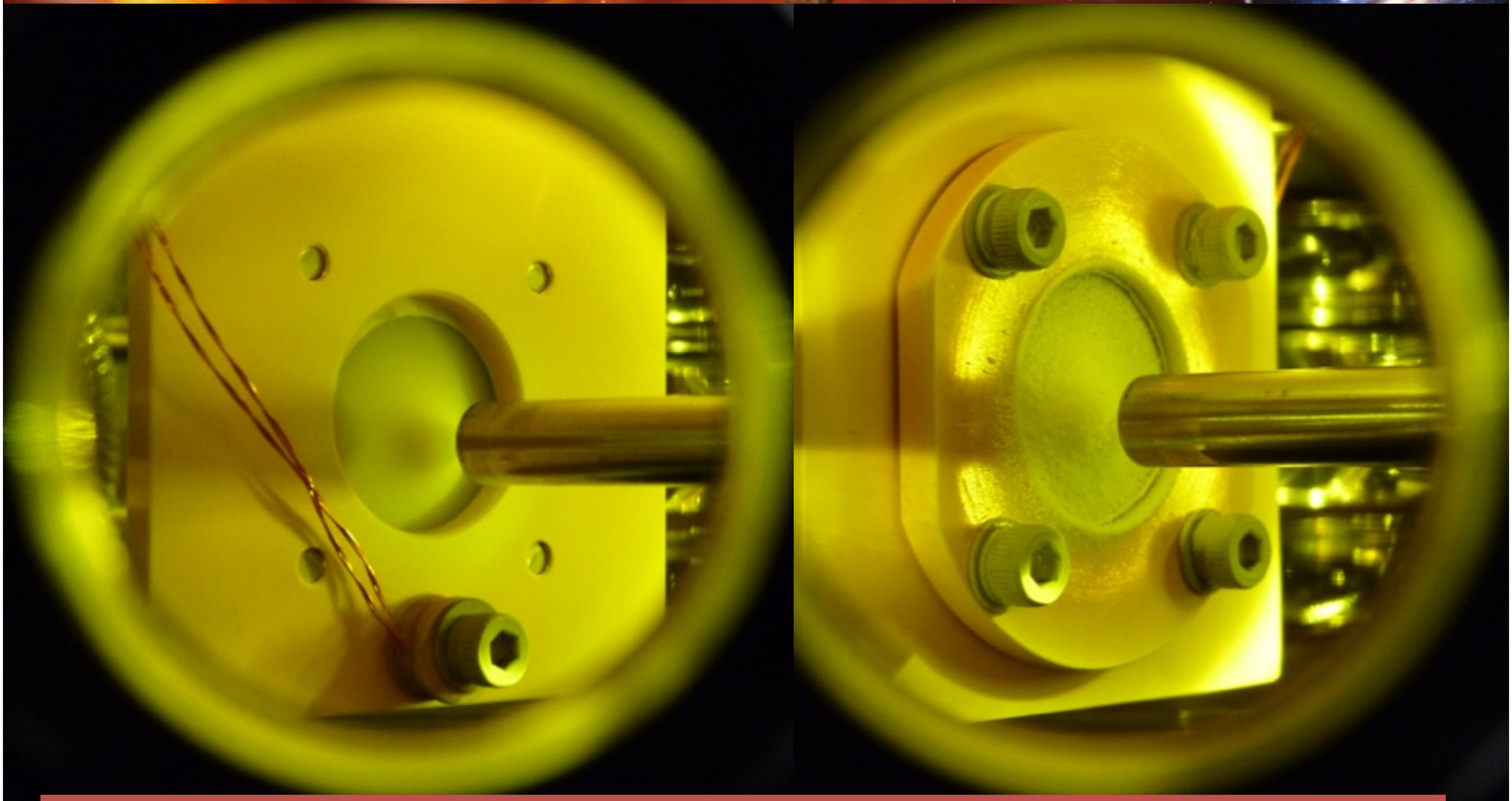
# Amorphous vs. Crystalline $H_2O$ Ice

A Comet's Nucleus – What is it?
Amorphous or Crystalline?

Amorphous Ice Traps Large Amounts of Impurities!

Crystalline Ice Expels Impurities!

# Macroscopic Amorphous Ices in the Lab: Simulating Interstellar & Comet Ices

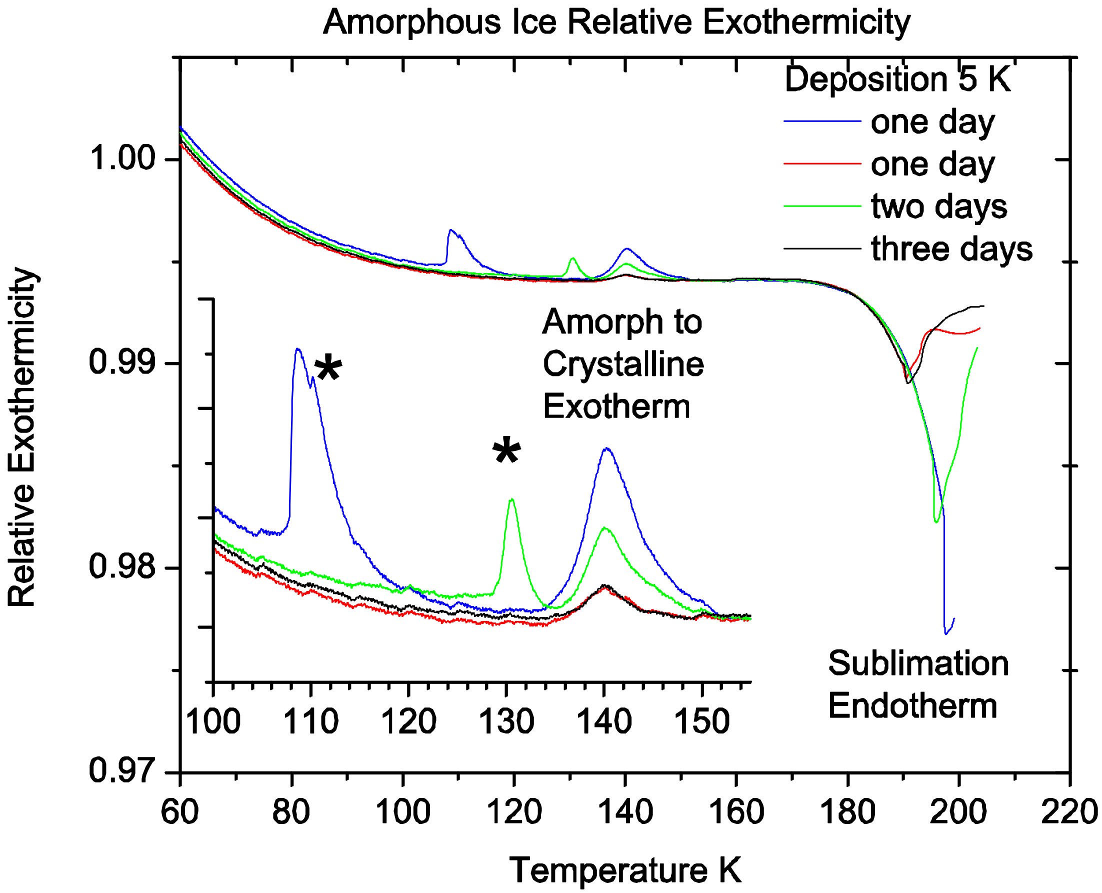


150 K Deposition (Crystalline)

5 K Deposition (Amorphous)

# Amorphous to Crystalline – Exothermicity

**Impurities may change exothermic to endothermic (amorphous to crystalline) transition – to be confirmed in the laboratory**




Robert Wagner and Murthy Gudipti (2013) to be published

Kochi & Sirono GRL 28(2001)827

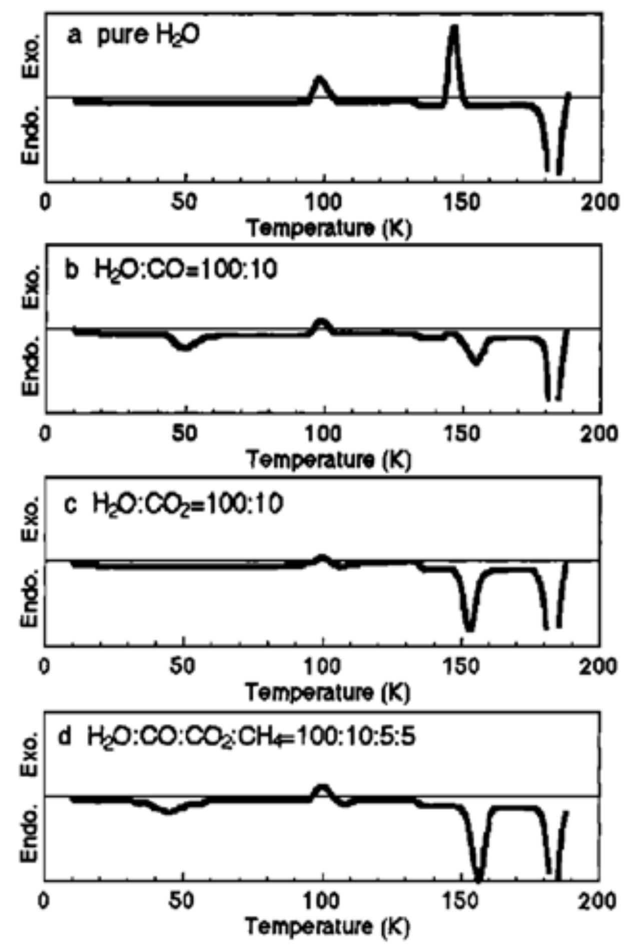
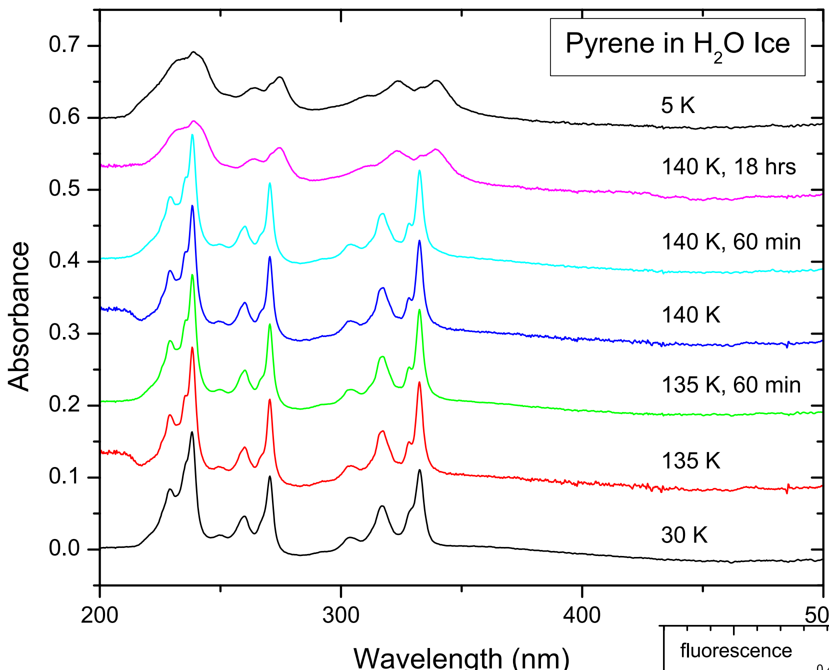
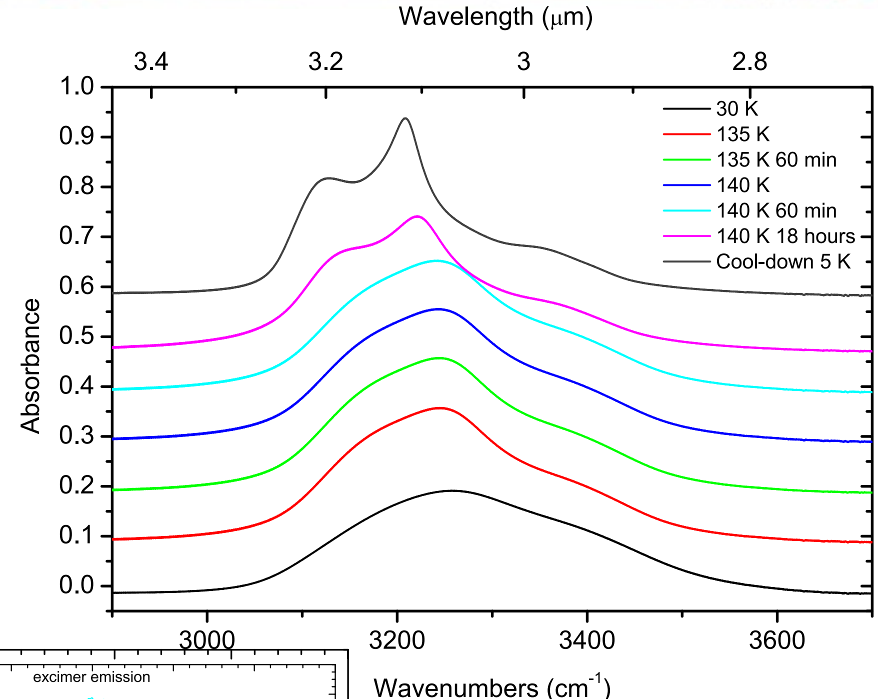



**Figure 2.** DTA curves of pure (a) and impure (b-d) a-$H_2O$. Endo., endothermic; Exo., exothermic.

# Crystalline Ice NOT a Good Host for Impurities

## 1:500 Pyrene in H2O Ice

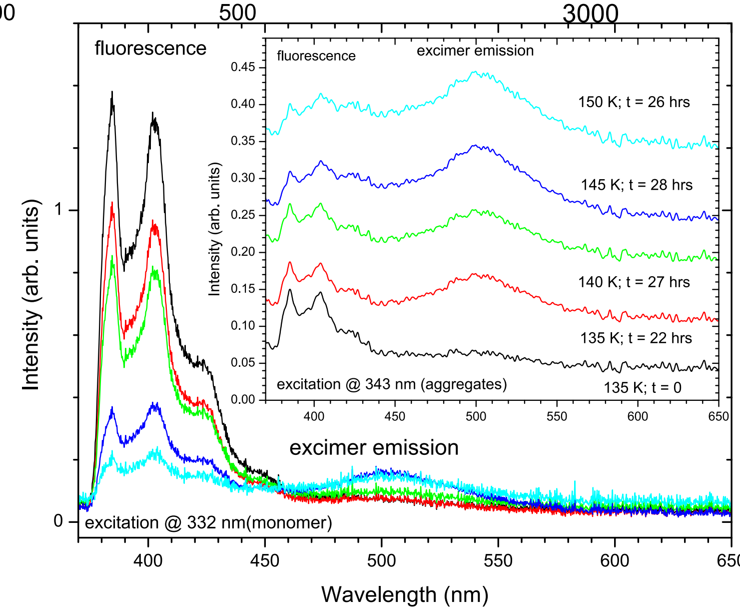



UV - PAH

IR - Ice

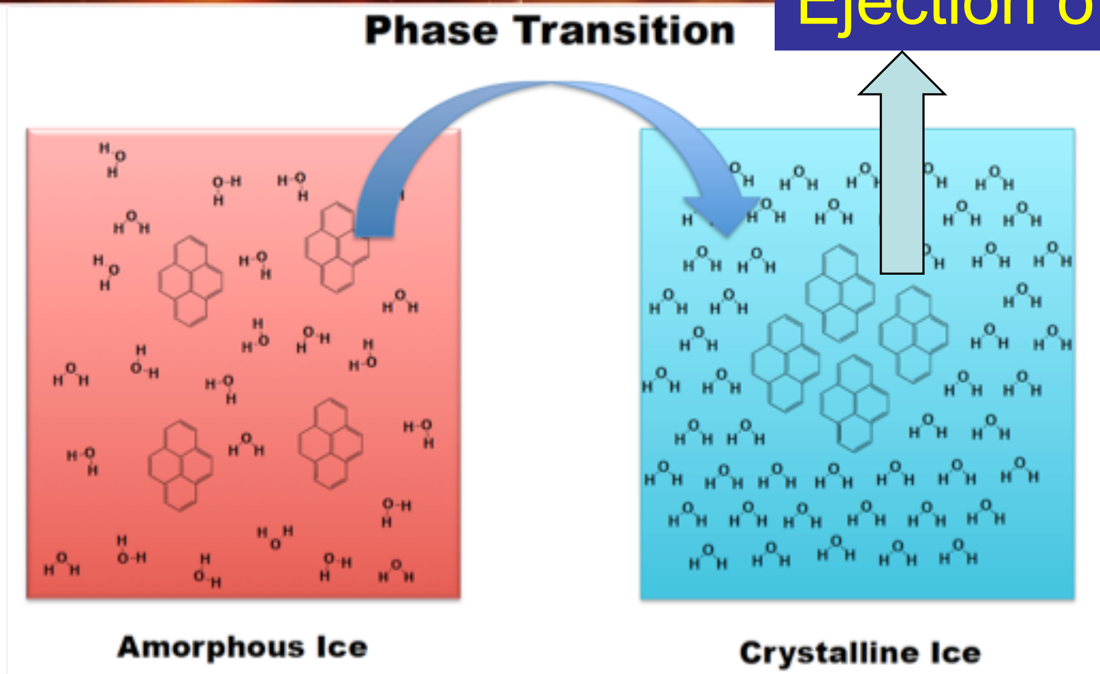
Flu - PAH



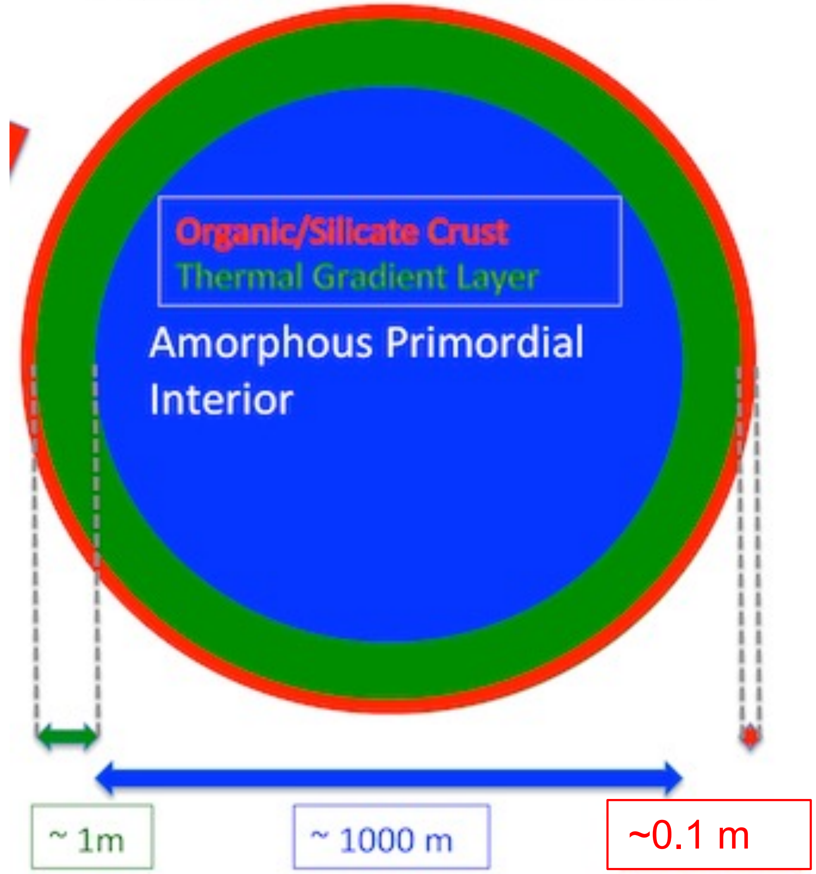

Lignell & Gudipati
J. Phys. Chem A.
119 (2015) 2607

# Is there a Crystalline-Ice-Dust-Sintered Mantle?

Ejection of Impurities




Processed ice ~ 1m
Unprocessed primordial ice >1m

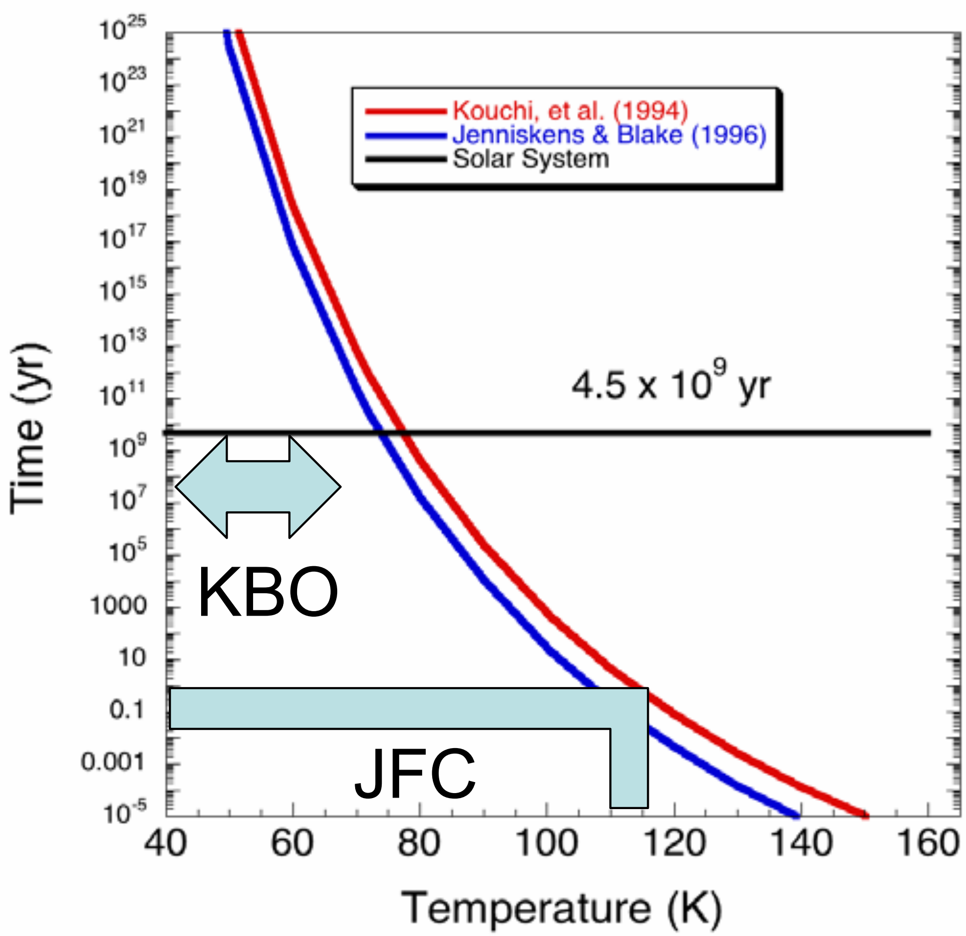



Comet CG/67P

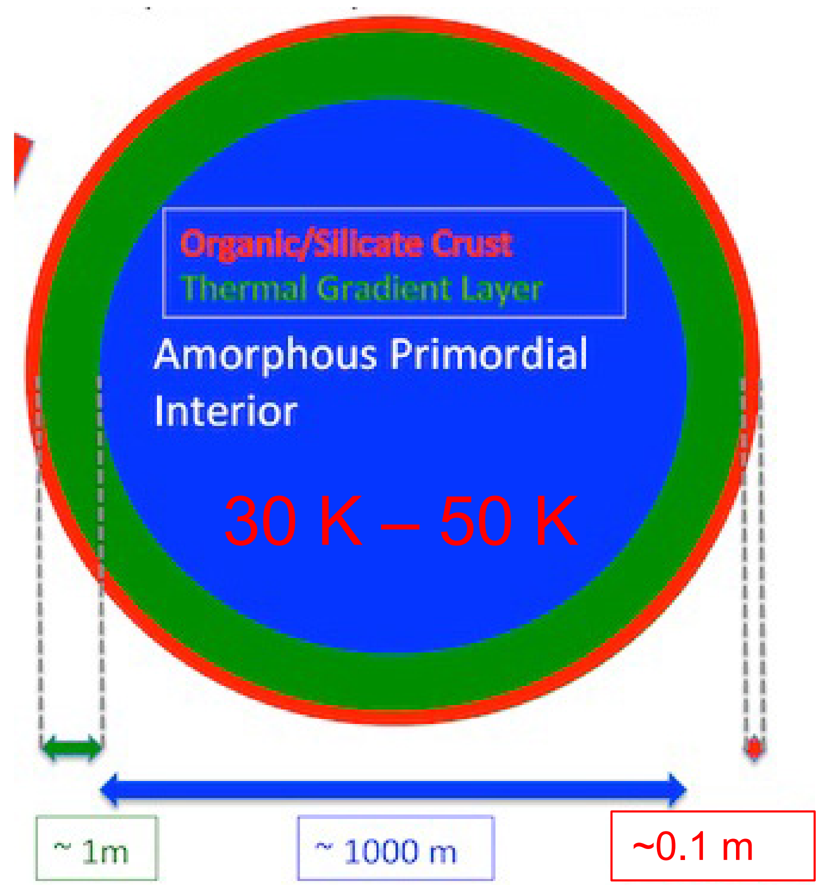
Lignell & Gudipati J. Phys. Chem A. 119 (2015) 2607

# How Primitive is a Comet's Interior?

## How Thermally Equilibrated are Comets?




Mastrapa, Grundy, Gudipati (Solar System Ices 2013)




Crystalline-ice-Silicate Crust?

# Amorphous vs. Crystalline $H_2O$ Ice

More Laboratory Studies on
Volatile Trapping of Crystalline Ice

It is likely that $O_2$ and $NH_3$ bond strongly with $H_2O$

# Trapping of Volatiles in $CO_2$ Ice

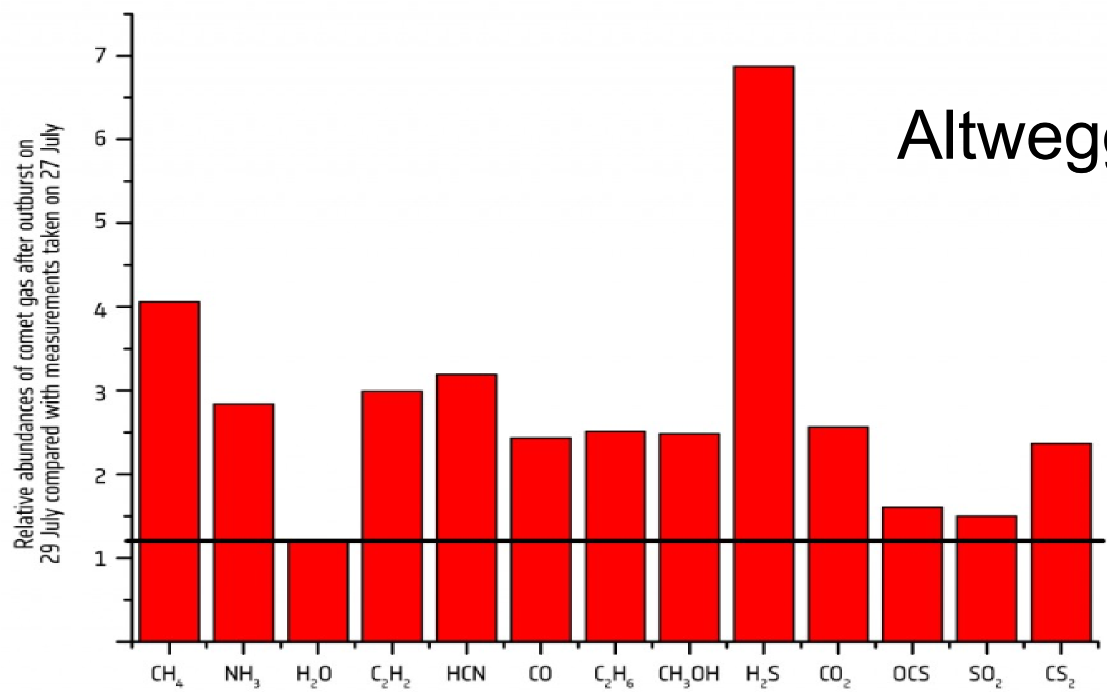
$CO_2$ is up to 20% of H2O

Can form Separate $CO_2$ Ice Domains

# Where are the Volatiles Trapped? $H_2O$-Ice or $CO_2$-Ice

## During Outbursts from Interior $CO_2$ is accompanied by Volatiles

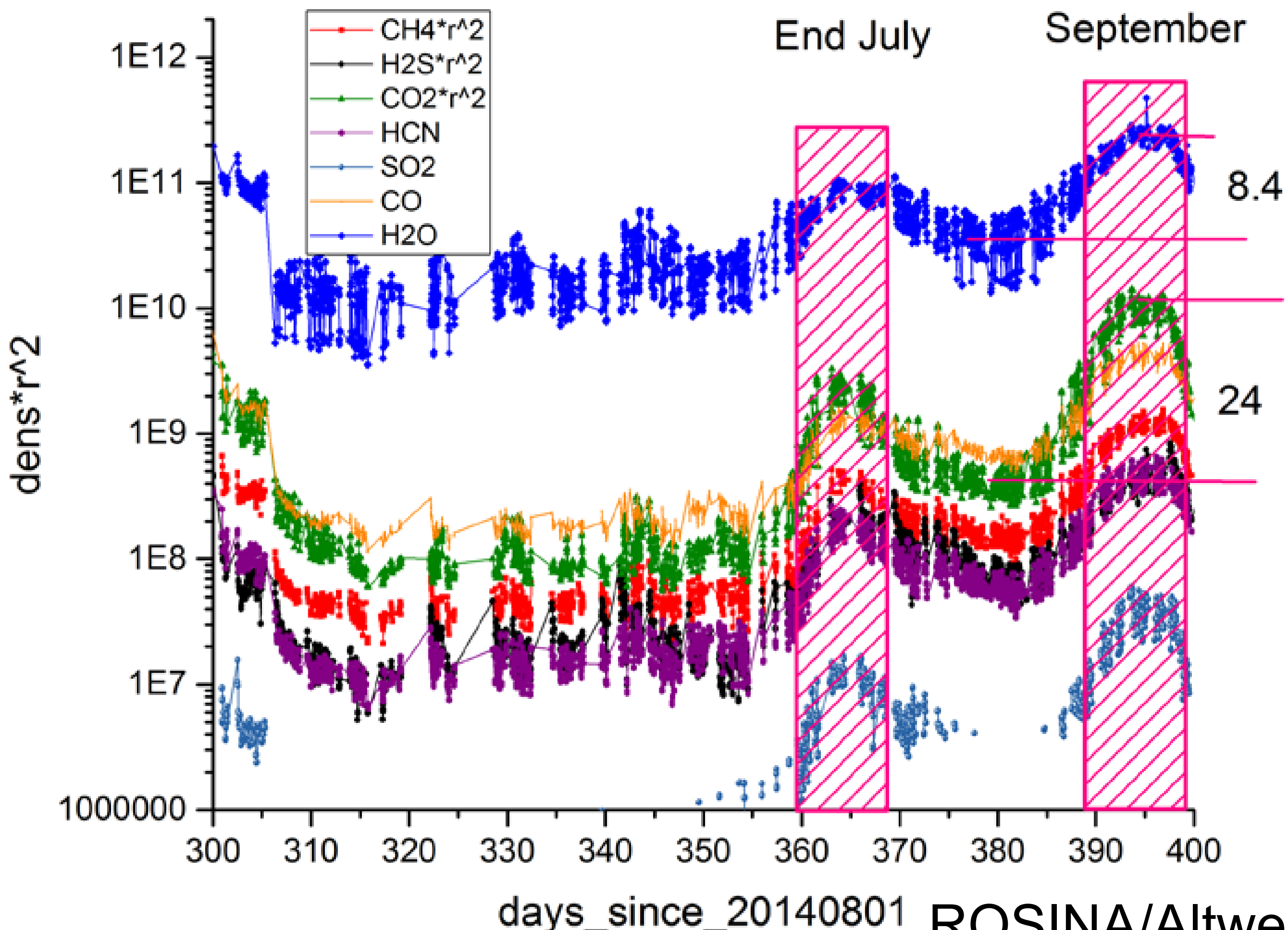
→ ROSINA MEASUREMENTS OF COMET GAS FOLLOWING OUTBURST




Altwegg et al.,

During an outburst of gas and dust from Comet 67P/Churyumov–Gerasimenko on 29 July 2015, Rosetta's ROSINA instrument detected a change in the composition of gases compared with previous days.
The graph shows the relative abundances of various gases after the outburst, compared with measurements two days earlier (water vapour is indicated by the black line).
Credits: ESA/Rosetta/ROSINA/UBern/ BIRA/LATMOS/LMM/IRAP/MPS/SwRI/TUB/UMich

Production rates of the volatiles between July and September 2015 increased by a factor 24, water by a factor 8.4. This is most probably also due to the outbursts, which release mostly species more volatile than water.




ROSINA/Altwegg et al.

# Trapped vs. Segregated Volatiles

<<1% = Trapped (Depleted Super Volatiles)

1-5% = Trapped (with moderate binding with host)
$H_2O/NH_3$ or $H_2O/O_2$

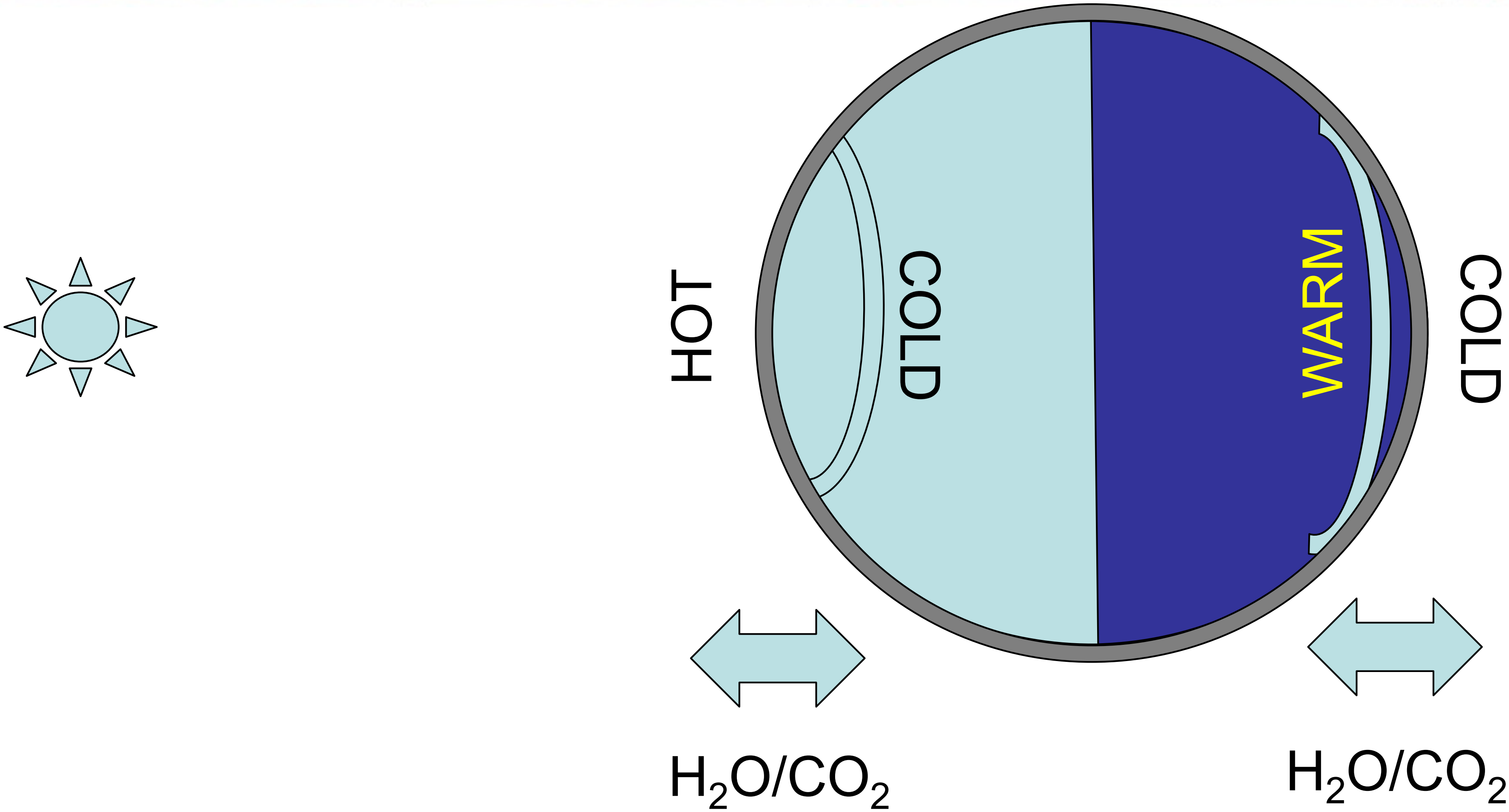
5 – 20 % = Segregation domains ($H_2O$ vs. $CO_2$)

No Laboratory Studies on Hand to Determine How $CO_2$ Ice Traps Volatiles

# Trapping of Volatiles in $CO_2$ Ice

**Laboratory Work is Needed**

# Outbursts from Pressurized Pockets?




G. Filacchione et al., Science (2016)
Seasonal exposure of carbon dioxide ice on the nucleus of comet 67P/CG

# Conclusions

Cometary Nucleus of 67P/CG is Depleted in Super Volatiles:

Reactive/Polar/Hydrogen-bonding molecules such as $O_2$, $NH_3$, HCN, $CH_3OH$, should go with $H_2O$ ice.

$CO_2$ ice may provide better trapping for non-polar molecules such as CO and $CH_4$ etc.

**Crystallization energy of $CO_2$ ice is far less than $H_2O$ ice, providing more room for trapping other species – to be tested in the laboratory!**

**Is “Activity” from Thermally Processed Nucleus??**

# Role of Silicate Grains

NO Laboratory Yet involving
Silicate Dust Grains + $H_2O$ + $CO_2$ + Impurities
Ice-Coated Silicate Dust!

# Laboratory Studies Needed

- Exothermicity of Amorphous Water Ice with Impurities
- What is the survivability of Ar, Kr, $O_2$, $N_2$, CO, $CH_4$ (Supervolatiles) – from Pre-Solar to Present Day (10 K – 40 K – 120 K)?
- How/Where are the refractory complex organics produced?
- $H_2O$ ice (amorphous vs. crystalline) and impurities
- $CO_2$ ice (crystalline) and impurities
- Dust/Ice Simulations at 30 K – 150 K
- How does the interior of a JFC comet work? Like Pressure Cooker?
- …

**Comet Nucleus Laboratory Research Consortium**

# Acknowledgments

Thanks:
Co-Workers at JPL/ISL;
Funding: Rosetta (US), JPL, NASA R&A
Thank YOU!